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# BEHAVIOR OF NOTCHED FIBERS IN LONGITUDINAL TENSION



by

Dusan C. Prevorsek, Arthur B. Coe
and W. James Lyons





May 1965

# BEHAVIOR OF NOTCHED FIBERS IN LONGITUDINAL TENSION

## Introduction

Plastic deformation taking place during drawing of fibers, and creep occurring before their rupture, is often only apparently irreversible and cannot be regarded as flow. Fiber growth in the direction of applied stress involves primarily the orientation of molecules and crystalline domains, which is accompanied by partial unfolding and reorganization of crystallites [1]. This process leads to an increase of polymer-chain dimensions in the direction of the applied load,while the number of molecules intersecting a fiber cross section remains essentially unaffected. In an overall manner this process resembles somewhat that which takes place during the extension of rubber. However, with fibers, the deformation is opposed by large viscous forces, so that the energy applied for deformation is irreversibly lost as heat. It is interesting that this kind of deformation can, to a large extent be reversed if fibers are heated to near their melting point [2].

The improvement in orientation achieved by the stretching of fibers leads to an improvement in lateral packing. Because the chain molecules are better aligned axially, the number of effective bonds between them is increased. Consequently the stress required for further plastic deformation increases as the strain on the fiber increases. This effect is liable to be

overlooked in a conventional stress-strain diagram in which stress is not corrected for the reduction of fiber cross-sectional area during stretching.

When a critical extension is reached, the stress required for plastic deformation becomes so large that further elongation can be achieved only by molecular rearrangements leading to structural features that result in lower density [3,4]. This stage is characterized by the appearance of strain bands, a phenomenon which usually becomes noticeable shortly before rupture. Thus, it appears that despite considerable plastic deformation preceding fiber rupture, this cannot be regarded as a result of a flow process (chain slippage) leading to a reduction of the number of molecules intersecting a plane perpendicular to the fiber axis; more often the breakdown seems to be initiated from a crack.

A theory of fatigue in cyclic longitudinal tension, based upon this concept, was developed by Prevorsek and Lyons [5], and one of fiber strength by the former [6]. The derived expressions included a parameter, fracture surface energy (or fracture surface work), the value of which has not yet been estimated for fibers. A study has therefore been undertaken to obtain information on the propagation of cracks in fibers, and to explore the possibility of determining fracture surface energy on highly oriented systems such as monofils.

## Experimental

Chordal notches[1] were cut into heavy monofils by means of the device shown in Figure 1. The apparatus consists of a razor blade R, which moves freely in vertical slots in the upright members U. The fiber that is to be cut is placed in the semi-circular groove G in the lower plate P of the device. In order to prevent slipping or rolling of the fiber during cutting, the diameter of the groove should be about that of the fiber. The micrometer screw M, mounted on the upper plate B, is used to press the razor blade against and into the fiber, and to control the depth of the notch.

Circumferential notches were cut in monofils by rolling them along the edge of a razor blade fixed in a vertical slot in a brass block, the edge being a known distance above the horizontal surface of the block.

Measurements of notch depth and the observation of crack growth under stress, were done under a microscope with the aid of the metallic manipulator shown in Figure 2. During the measurements this apparatus is mounted on the rotating table of the microscope.

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[1] A chordal notch is one in which the root (or tip) is a straight line connecting the extremities of an arc of the circle outlining the fiber cross section.

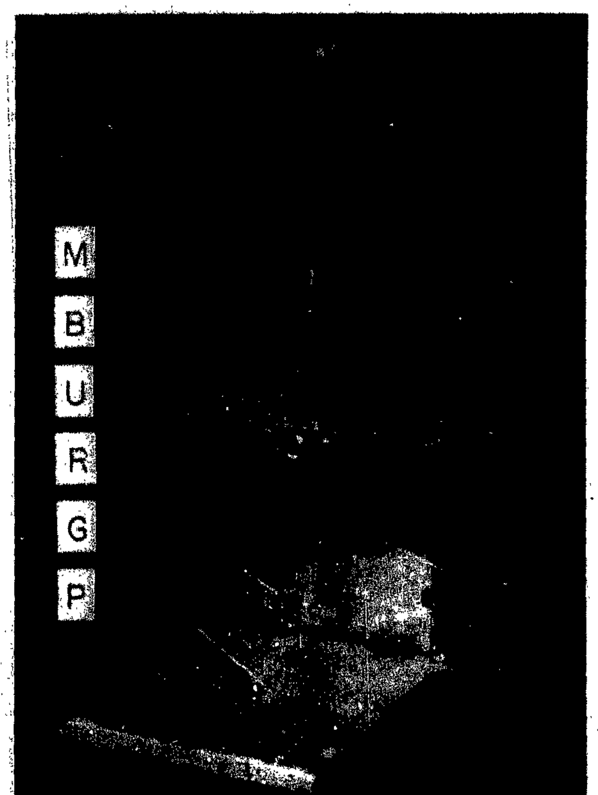


Fig. 1. Device for cutting chordal notches of controlled depth in monofils.

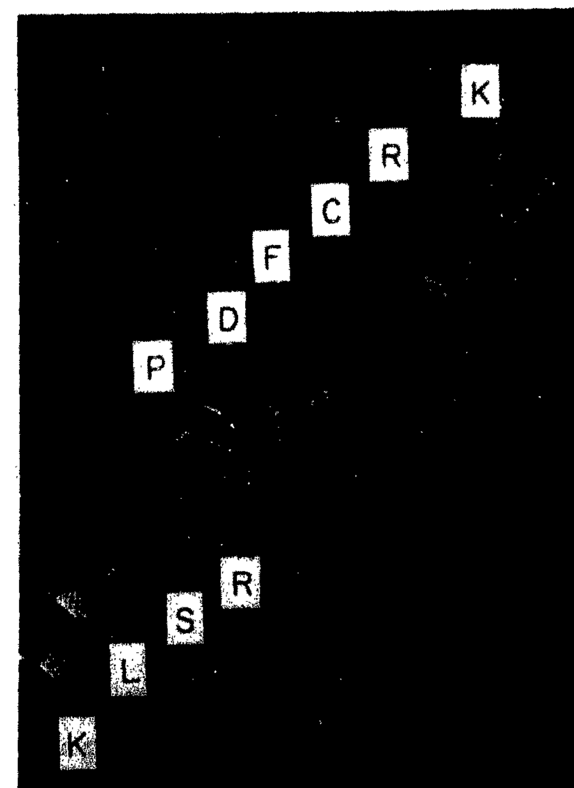


Fig. 2. Manipulator for turning and tensioning monofils during microscopical examination.

The manipulator consists of a rectangular frame F, through the ends of which extend freely rotatable rods R, having knurled knobs K at their outer ends. On the inner ends of these rods, which are coaxial, are clamps C and D for holding the fiber specimens under observation. One of the rotatable rods passes through and is engaged by the horizontally movable, vertical plate P. Movement of this plate, and hence the clamp D, is controlled, through a lead screw S, by means of a third knurled knob L. This arrangement permits the observation of the fiber from all sides and allows the application of tension, or of torsion, if one clamp is rotated with respect to the other. Extension of the specimen may be measured by means of a scale attached to the movable plate.

The depth of the notch is determined with a filar micrometer eyepiece. In order to make the tip of the crack discernible, the specimen is first subjected to a small longitudinal strain, and rotated around its axis until the root of the crack is aligned parallel to the optical axis of the microscope. In applying the stress before the measurement, care should be taken that this operation does not alter the depth of the crack. It was found that with the exception of very shallow notches, the depth estimated from the displacement of the micrometer head on the notching device usually agrees well with the depth measured under the microscope.

## Results and Discussion

### Geometry of notches under strain

The presence of a very narrow and sharp crack in a specimen decreases its strength more than would be expected from considerations based on the reduction in the cross-sectional area. Such a crack acts as a stress raiser. Because of this effect the stress at the tip of the crack is usually much greater than the locally applied stress. This concentration of stress is expressed as stress concentration factor $q$, defined as the ratio of maximum stress at the notch to the applied stress. The value of $q$ depends both on the size of the crack or notch and its geometry. This value for a narrow, irregular crack having an elliptical root, according to Inglis [7], is given by

$$q = 2\sqrt{\frac{a}{r}} \qquad (1)$$

where $a$ is the depth of the crack and $r$ is the radius of curvature at the tip.

When a specimen is subjected to strain, the plastic deformation that occurs is primarily in the region of high stress. Thus, with notched specimens, the largest deformation is expected to occur at the root of the crack. The stress field tends to increase the radius of curvature of the root which, according to Equation 1, leads to a reduction in the stress concentration factor as the load on the specimen increases. In order to obtain information about the

magnitude of this effect in fibers, a microscopical study of changes in the shape of the notch in specimens subjected to increasing strain has been undertaken.

In Figure 3 are shown the profiles of a chordal notch in a nylon 6 monofil at various strains imposed on the specimen. Considerable increases in the radius of curvature occurring at the root of the crack before the crack starts to propagate are

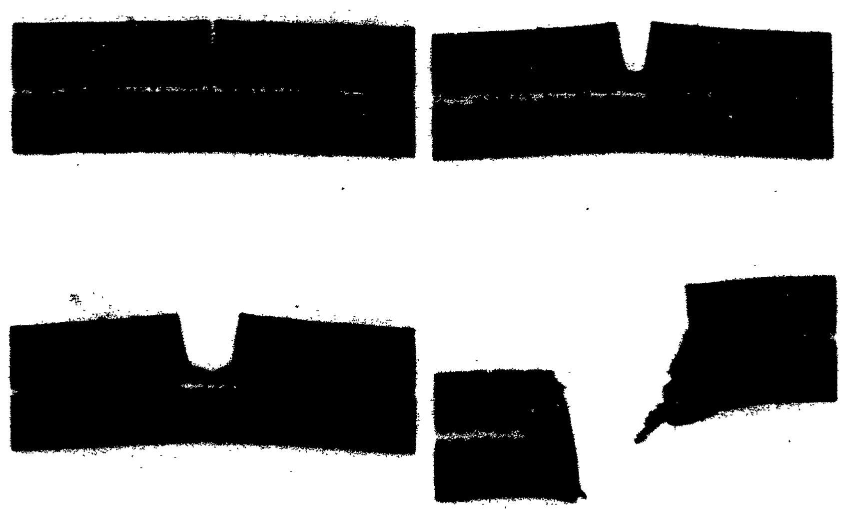

Fig. 3. Profiles of a chordal notch in a nylon 6 monofil at various strains on the specimen, up to rupture.

worth noting. The large changes in the curvature of the root produced by small loads, reveals an important property of fiber structure, namely that it is difficult to form an imperfection which would induce a permanent high concentration of stress. This

essential property of fibers is associated with low intermolecular and (in some cases) also low inter-fibrillar forces, both of which allow easy lateral rearrangement. During breakage of polymer chains or fibrils, longitudinal strain may lead also to considerable slippage along the direction of orientation. Part of the fiber strength and toughness is attributable to the inherent weakness of fibers perpendicular to the orientation of polymer chains. If the intermolecular forces are increased (e.g. by introduction of chemical cross-linking), the structural rearrangements leading to a release in stress around stress raisers becomes more difficult, which in turn results in a reduction in strength [8].

Another interesting feature revealed by the photomicrographs shown in Figure 3 is the high extensibility of the notched section of the fiber. Although the breaking extension of the undamaged fiber amounted to only 30%, the section containing the notch seems to elongate much more before it ruptures. This phenomenon is observed also on specimens having circumferential notches. Such a fiber subjected to increasing strains is shown in Figure 4. It has also been found in specimens of various draw ratios that plastic deformation occurring at the notch when stress is applied, decreases with improved orientation.

Near-brittle breaks of flattened highly oriented nylon 6 monofils are shown in Figures 5 and 6. In this particular case

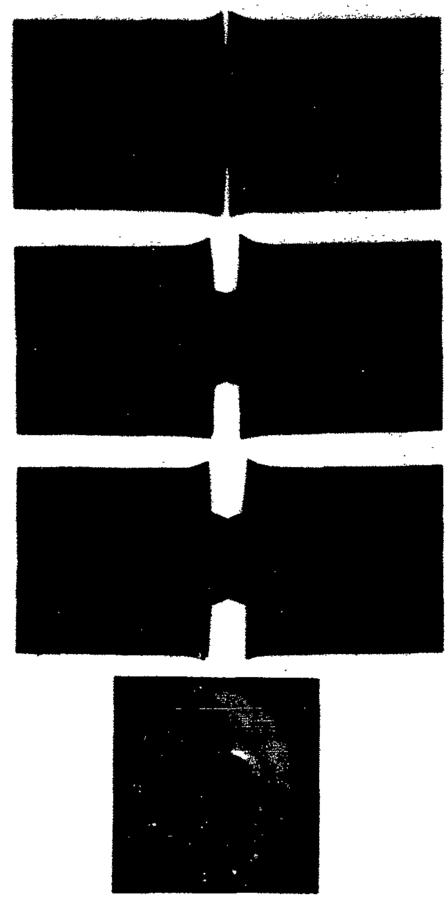

Fig. 4. Profiles of a circumferential notch in a nylon 6 monofil at various strains; and an end view after rupture at the notch.

the extent of flow involved in rupture seems to be affected little by the fact that one fracture was initiated from a notch (Figure 5) and the other from a linear hole cut through the center of the flattened specimen (Figure 6). This observation, however, is not necessarily applicable to fibers where the structure of the skin differs considerably from that of the core. In such a case the rupture initiated at the interior of the fiber could involve different mechanisms from those where the origin is on the surface.

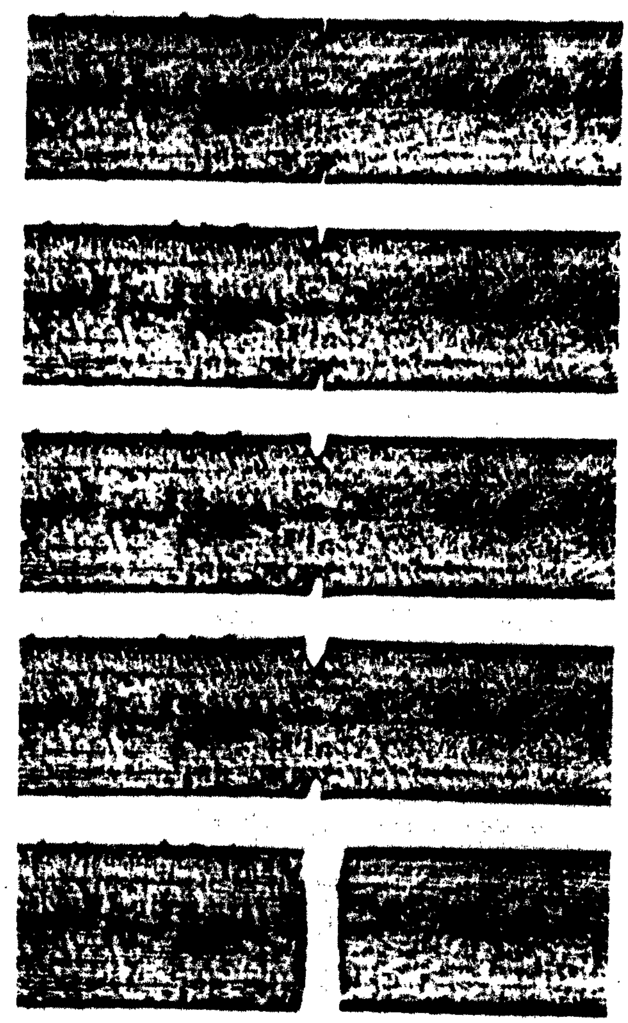

Fig. 5. Profiles of notches in flattened nylon 6 monofil at various strains, up to rupture.

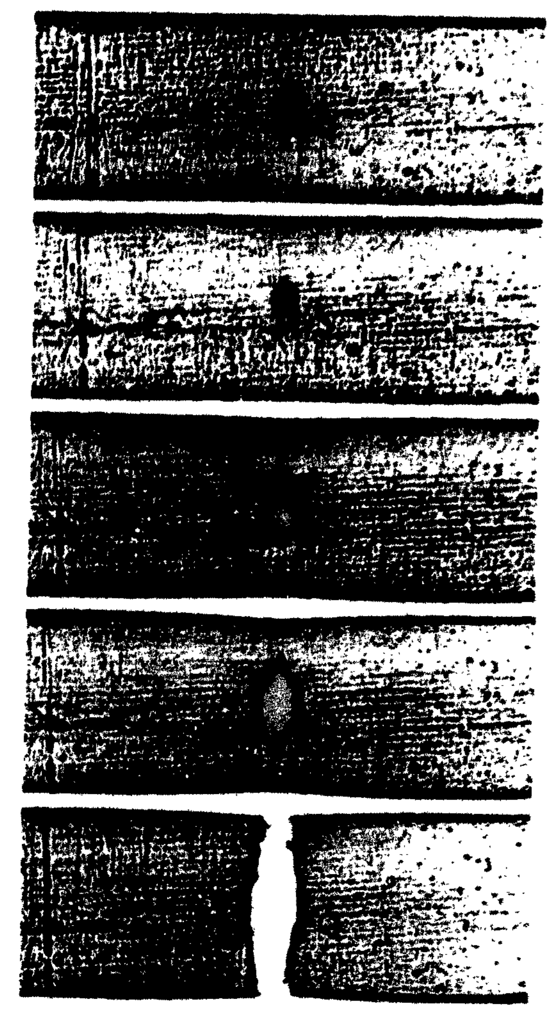

Fig. 6. Views of puncture in flattened nylon 6 monofil at various strains, up to rupture.

Further information about the extent of plastic deformation involved in rupture can be obtained from the examination of the surface of broken ends of fibers containing circumferential notches.

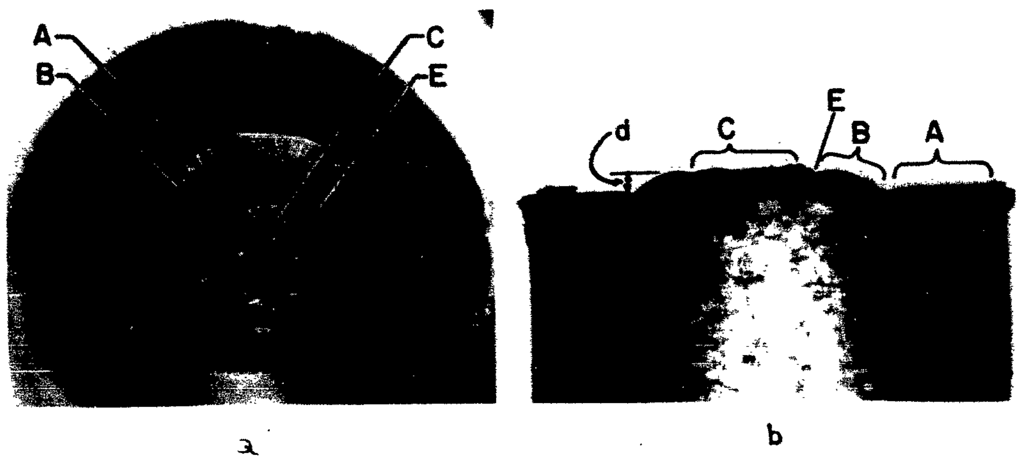


Fig. 7. Broken ends of nylon 6 monofils ruptured at circumferential notches: a. oblique view; b. profile of longitudinal section through broken end.

In Figure 7 are photomicrographs of two aspects of the broken ends of notched nylon 6 filaments. The surface of the break can be divided, with regard to its appearance, into three areas. The area A cut with the razor blade, usually shows some roughness and traces of the cutting edge. The area B, formed during the slow propagation of the crack, is very smooth and rises considerably above the level of area A cut with the knife. The distance "d" indicated in Figure 7b reflects the magnitude of the flow occurring during the rupture. The central area C formed during the rapid propagation of the notch at the instant of rupture is rough and

is separated from area B by a narrow valley E. It is believed that this valley is formed as a result of a sudden release in stress energy when the fiber is ruptured. Thus, the diameter of the valley is probably an indication of the critical depth of the notch. The difference in the appearance between areas B and C implies that the mechanism operating in the slow propagation of the crack must be different from the one operating during the catastrophic rupture of the specimen.

Estimation of inherent flaw size

The breaking stress of heavy monofils is usually negatively correlated with the size of the monofils. This is shown in Figure 8, which is based on conventional tensile tests, (at 70 °F; 65% RH) of fifteen specimens each, on nylon 66 monofils of four

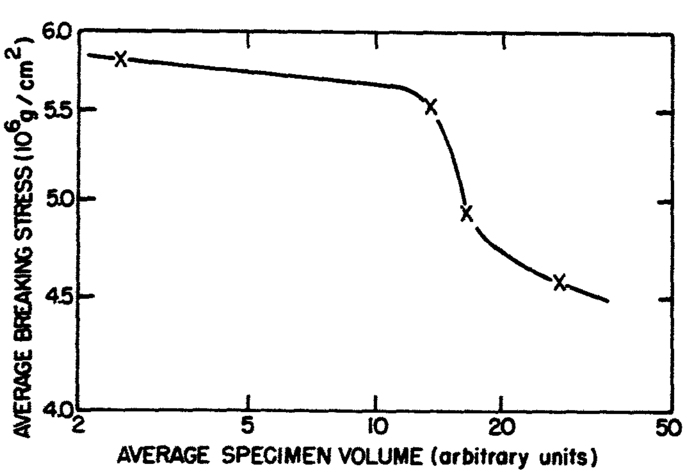


Fig. 8. Average breaking stress of nylon 66 monofils as a function of specimen volume.

different diameters: 7, 16, 18 and 23 mils. For comparison with statistical theory the average breaking stress is plotted as a function of the volume of the specimens, on logarithmic scales. The result indicates that the relationship is not linear, and that the dependence is greater than is to be expected from considerations based on extreme-value statistics and observed scatter[2]. It is supposed that breaking strength reflects the distribution of flaw sizes. The implication of the data shown in Figure 8 is, then, that when fibers of a particular polymer type, having various diameters, are spun under otherwise uniform conditions, there is a tendency for an increase in the inherent flaw size as the fiber diameter (and volume) increases.

Similar tensile tests were conducted on circumferentially notched specimens of one of the nylon 66 samples (23-mil diameter),

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[2] For a scatter conforming to the Wiebull distribution, the logarithm of the most probable value (mode) of the tensile strength should decrease linearly as the logarithm of the specimen volume increases [9], with the slope of the graph equal to $-1/k$, where $\underline{k}$ is a parameter reflecting the width of the distribution. In the above considerations it is assumed that the average strength is proportional to the mode.

as well as of two nylon 6 samples. The breaking stress of these notched samples was calculated on the basis of the cross-sectional area that was effective in the test, i.e., the area of the cross-section left intact after the notching to a certain depth. The results, presented in Table I, indicate that the notched samples generally have higher breaking strengths (calculated in this manner)

Table I. Breaking strengths of unnotched (control) and circumferentially notched nylon monofils ($70^{o}F$; 65% RH)

| Sample Description | Average effective area ($10^{-4}$ $cm^2$) | Average breaking strength ($10^6$ $g/cm^2$) |
|---|---|---|
| Nylon 6 | | |
| Control (13-mil) | 8.5 | 4.8 |
| Notched (" ") | 2.9 | 6.0 |
| Control (28-mil) | 40.3 | 4.4 |
| Notched (" ") | 6.8 | 5.0 |
| Nylon 66 | | |
| Control (23-mil) | 27.6 | 4.6 |
| Notched ( " ") | 16.2 | 4.6 |
| Notched ( " ") | 2.3 | 6.8 |

than the unnotched controls. Evidently, the artificial notches have blunt or flat roots, so that $\underline{r}$ in Equation 1 is large in comparison with $\underline{a}$ and the factor $\underline{q} \approx 1$. Again, it would appear that,

insofar as breaking strength reflects the distribution of flaw sizes, larger flaws tend to be associated with larger effective cross-sectional area (and specimen volume).

In order to explore quantitatively the effect of chordal notches on the tensile strength of fibers, nylon 6 monofils were cut to various depths and tested for breaking load. The results are shown in Figure 9. Each point represents the mean of about nine individual measurements. The interesting feature of this plot is the fact that the curve drawn through the data points intersects the value of the strength of the unnotched control at a value of the abscissa larger than zero. On the basis of this observation, it may be concluded that this particular sample has inherent flaws (cracks, or other types), giving rise to stress concentrations equivalent to those of a chordal notch of 0.003-in. depth. If notches smaller than this size are cut into this sample, specimens tested do not always fail at the notch and their strength is equal to that of the undamaged control.

## Summary and Conclusions

The experiments on notched fibers indicate that part of the fiber strength has to be attributed to its weakness perpendicular to the fiber axis, which allows easy lateral rearrangements of polymer chains. As a result, concentrations of stress associated with pre-existing cracks are usually greatly reduced before the

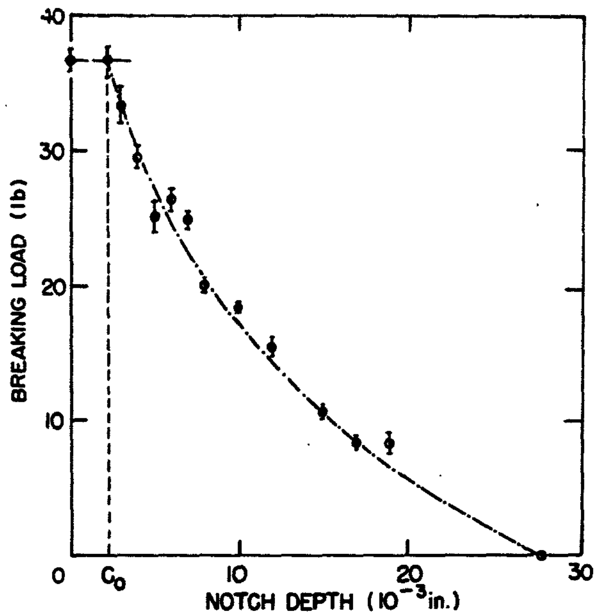


Fig. 9. Effect of depth of chordal notches on breaking load of nylon 6 monofils of 28-mil diameter. The vertical bars appended to each data point represent the 95% confidence intervals. $C_o$ is the depth of notch equivalent to an inherent imperfection.

cracks start to propagate. If the strength of notched fibers is plotted against the depth of the notch, an estimate of the size of inherent imperfections can be obtained. It is believed that this quantity may be used for the numerical assessment of the quality of processing conditions.

The examination of the surface of broken ends of fibers containing circumferential notches confirmed the predictions of the afore-mentioned theories proposed by Prevorsek and Lyons that there is a critical size of crack at which an abrupt increase in the rate of crack growth is to be expected. It seems that similar experiments may lead to an independent estimate of the critical size of a macrocrack, and thus permit quantitative verification of the theories mentioned above.

Attempts to estimate the fracture surface work from the data shown in Figure 9 could not be made, because the relationship between the strength of a specimen and the depth of a crack has not yet been worked out for the case of a circular bar having a chordal notch. Work by one of us (D.C.P.) is in progress to derive such an expression, which would then permit the determination of fracture surface work on fibers.

## Acknowledgements

The authors wish to record the participation of Polly K. Way in this research. She prepared the specimens and performed the mechanical-property measurements reported herein. The details of design and the construction of the notching and stretching devices were the work of Harold Lambert.

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